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An experimental method to determine the heat transfer coefficient between fine fluidized particles and air via changes in magnetic properties

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Abstract—A new experimental technique to evaluate gas–particle heat transfer coefficients in fine particle fluidized beds is described. The technique makes use of the change in magnetic properties of a low curie-point ferrite to track the changing temperature of a cold sample of particles injected into a hot fluidized bed. The bed is 28 mm in diameter and is surrounded by a detection coil which is capable of sensing the change in magnetic properties of the material comprising the bed. A model is developed which relates the output voltage signal from the detection coil to the gas–particle heat transfer coefficient. Preliminary experimental results are compared with the model.

INTRODUCTION

DURING the last 30 years extensive work has been carried out in determining gas–particle heat transfer coefficients in fluidized beds. The results of this work are summarized in Fig. 1. From this figure it is seen that as the particle Reynolds number is reduced below 100 (fine particle systems) the reported experimental particle–gas heat transfer coefficients, h_p, all lie increasingly below the Ranz and Marshall [18] equation for single particles, as low as one thousandth of the expected minimum, and also appear to have no limiting value as $Re_p \to 0$.

There is much discussion about this disagreement, particularly because so far only indirect methods have been used to evaluate h_p for fine particles. However, this whole question can be resolved once and for all by a direct measurement of h_p, say by inserting a thermocouple into a particle and dropping this particle into a fluidized bed at a different temperature. But how to do this for 100 μm particles (the size of a human hair) and even smaller.

The purpose of this paper is to describe an experimental technique and accompanying theoretical analysis for obtaining directly the changing temperature of particles during an unsteady-state operation. These particles can be in fluidized beds, or elsewhere and can be as small as desired, down to the micrometer range. From the transient temperature history of a particle the value of h_p can be obtained directly, i.e. without assuming the flow patterns for gas and solids within the bed.

This experimental technique makes use of the change in magnetic permeability of a solid to infer its temperature. In essence the technique consists of injecting a sample of cold ferro-magnetic particles into a hot fluidized bed. As the temperature of the injected particles changes so does the magnetic permeability. This change in magnetic permeability is detected by a coil surrounding the fluidized bed. The coil acts as one leg of an inductive bridge circuit which is connected to an impedance meter. The impedance meter (ferrite sensor) amplifies and conditions the signal from the coil and produces a voltage output which is proportional to the magnetic permeability of the material within the coil. In this manner the temperature history of the injected sample of particles can be recorded with time and from this information the heat transfer coefficient for the cold particles in the hot bed can be determined.

The material used in this experiment was TC-71 ferrite supplied by TDK, Inc., Japan. This material possesses very high magnetic permeability at ambient conditions but shows a rapid decrease in magnetic properties at temperatures greater than 70°C. The relative change in magnetic permeability of this material is shown in Fig. 2 and details of the experimental determination of this curve are given in ref. [19]. Since this material possesses a low curie temperature (approximately 70°C) the experimental technique outlined above can be implemented at a relatively low temperature, i.e. less than 100°C.

EXPERIMENTAL EQUIPMENT

A schematic diagram of the experimental setup is shown in Fig. 3. House air is fed to the two beds via a regulator and rotameter. Heating coils are placed on the inlet lines to both fluidized beds and are fed by a d.c. power supply capable of supplying up to 10 A of current. This system allows the fluidizing air to be heated up to approximately 100°C prior to entering the beds. The fluidizing air flows up through the beds and out to the atmosphere. Around each of the beds

NOMENCLATURE

A	constant in equation (4) [V]
A_1	constant in equation (1) [V]
B	constant in equation (4) [$V K^{-1}$]
B_1	constant in equation (1) [V]
C	constant in equation (4) [V]
C_1	constant in equation (1) [s^{-1}]
$C_{p,s}$	specific heat capacity of solid particles [$J kg^{-1} K^{-1}$]
D	constant in equation (4) [K^{-1}]
E	first-order exponential time lag function from equation (7) [—]
g	function relating ferrite output voltage to particle size, time and other variables defined in equation (5) [—]
h_p	particle–bed heat transfer coefficient [$W m^{-2} K^{-1}$]
L	characteristic length of particles (volume/surface area) [m]
P_x	mass fraction probability density fraction [—]
t	time [s]
T	temperature [K]
u_{mf}	minimum superficial fluidization velocity [$m s^{-1}$]
V	voltage response from ferrite sensor [V].

Greek symbols

ρ_s	density of solid particles [$kg m^{-3}$]
τ_1	time lag for electronic equipment [s].

Subscripts

c	curie
f	final
i	initial
in	input
out	output
∞	steady-state value
1, 2	minimum and maximum sizes in particle size distribution.

there is a detector coil which is connected to the ferrite sensor.

A more detailed diagram of one of the fluidized beds is shown in Fig. 4. The bed is constructed from a transparent butyrate plastic tube which is suitable for the temperatures used in this experiment. The bed was built with a double pass heating section around the inner tube to ensure as uniform a temperature as possible, and to minimize heat loss to the surroundings.

The direction of the flow of air through the bed is indicated in Fig. 4. After passing upward in the outer section and downward in the middle section the air finally passes upward through a packed bed of 1.5 mm glass beads held in place by two 200 mesh nylon distributor screens and through the fluidized bed of particles to the atmosphere. Four 127 μm type K thermocouples were used to sense the temperature at various points in the bed and the location of these is also given in Fig. 4.

The location and dimensions of the detector coil which is placed around the fluidized bed is given in Fig. 5. The coil consists of approximately 2300 turns of 34 AWG insulated copper wire arranged in four layers, and wound on a 44 mm i.d. butyrate tube, which is a tight fit over the fluidized bed unit. A helical copper ground shield is wound around the coil and the whole unit is wrapped with a protective sheath of mylar.

The electronic detection instrumentation, or ferrite

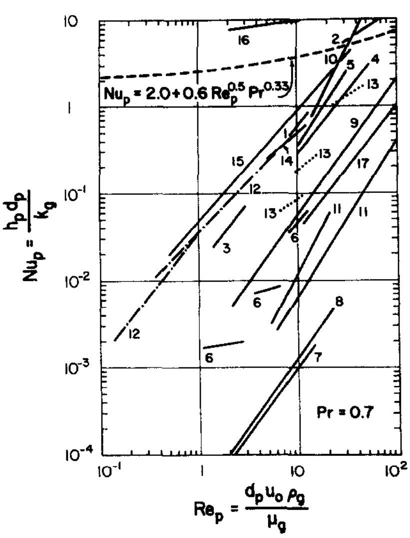

FIG. 1. Previously reported fluid–particle heat transfer data in fluidized beds (numbers next to curves are reference numbers).

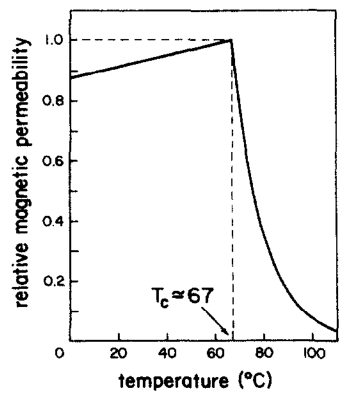

FIG. 2. Relative change of magnetic permeability with temperature for ferrite TC-71.

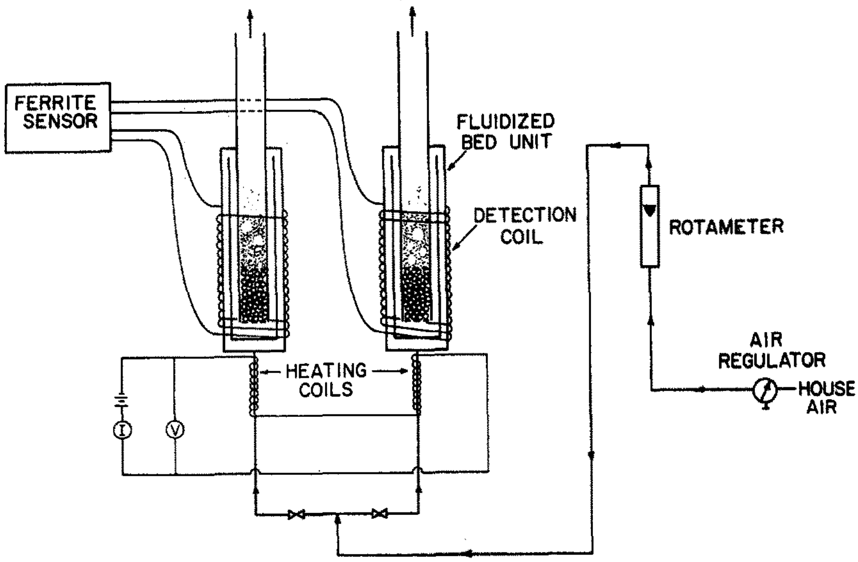

FIG. 3. Schematic diagram of fluidized bed system used in the heat transfer experiments.

sensor, is a modified metal detector similar to those used in airports. The details of the electronic circuitry are given elsewhere [19] but a brief description of its operation will follow.

The detector coils act as two legs of an inductive bridge circuit. A low distortion sine wave (950 Hz, and 20 V peak to peak) is delivered to the bridge and with no ferro-magnetic material in either coil the bridge is adjusted to give the same voltage in each leg. When a magnetic material is present in one of the coils the impedance of that coil changes and different amplitude sine wave voltages will appear in each leg

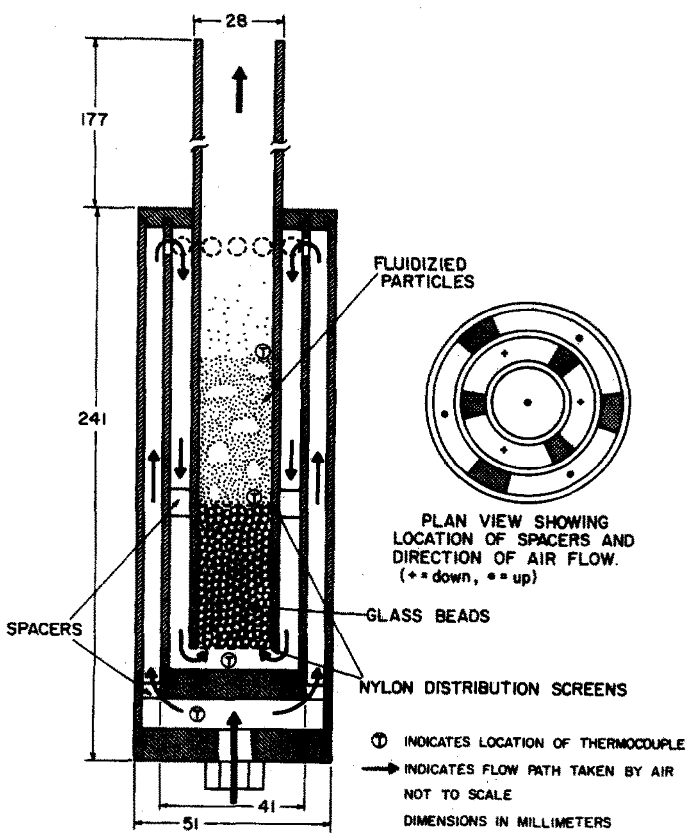

FIG. 4. Detailed diagram of fluidized bed assembly.

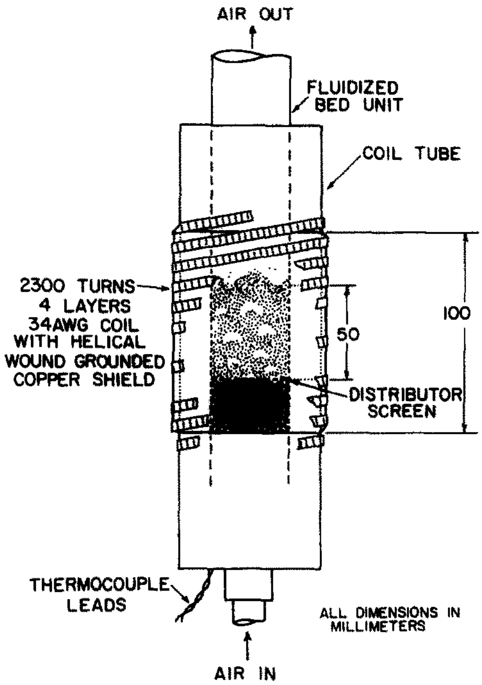

FIG. 5. Diagram of ferrite detection coil.

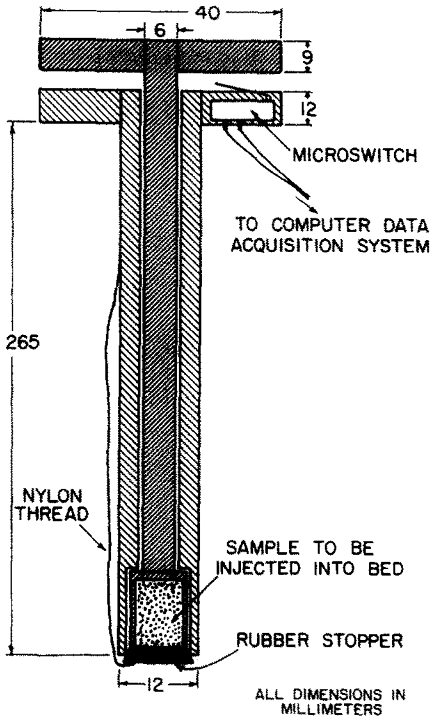

FIG. 6. Diagram of injection device used in the hot and cold mixing studies.

of the bridge. The difference between these two voltages is amplified and conditioned to give a steady voltage at the output of the ferrite sensor. This output voltage is directly proportional to the amount of magnetic material in the coil. Therefore, by injecting magnetic material into one of the fluidized beds while keeping the other one empty the magnetic permeability of the injected sample will be indicated by the output voltage from the ferrite sensor.

The device used to inject the sample of cold ferrite particles into the hot fluidized bed is illustrated in Fig. 6. This consists of a PVC plunger inside a clear plastic tube. Attached to the lower end of the plunger is a thin cylindrical tube into which the sample of ferrite particles is placed. A rubber stopper is force fit on the end of the outer tube to hold the particles in place, and is attached to the outer tube by a nylon thread. Stopper and injection device are removed quickly from the bed after injection of the particles. A 33 mm plastic disk is attached to the top of the plunger and when this is depressed it meets a similar disk secured to the top of the outer tube. A small roller type switch is countersunk into the lower disk such that when the plunger is fully depressed and the two disks meet the switch closes. This switch is connected to the computer data acquisition system, an IMI-ADALAB system installed in an IBM-PC computer. Thus closing this switch triggers the software program to start taking data from the ferrite sensor. In this way data is taken only when the injection device has been inserted into the bed and the particles have been released.

Ideally the material used in the hot fluidized bed should be the same ferrite as that injected into the bed. However, the bed temperature is maintained close to 90°C and from Fig. 2 it is evident that at this temperature the ferrite has a small but appreciable magnetic permeability. Since the ferrite sensor is very sensitive, e.g. a 150 mV signal is produced when only 0.5 g of ferrite (at 25°C) is present, the presence of this large mass (approximately 60 g) of hot ferrite produces a very large amount of background noise which masks the signal from the injected ferrite sample. For this reason it was decided to use a non ferro-magnetic material in the bed. The material chosen was zirconia which has a density approximately 20% greater than the TC-71 ferrite. Narrow size cuts of zirconia and ferrite between 328 and 116 μm were used in the experiments. The size of zirconia used in a given experiment was usually one size cut smaller than the injected ferrite to ensure that the minimum fluidizing velocities of ferrite and zirconia were approximately the same; for details see ref. [19]. The pairs of zirconia and ferrite particles used in the experimental runs are given in Table 1.

Table 1. Properties of the pairs of ferrite TC-71 and zirconia particles used in the experimental runs

System	Zirconia (Tyler screen size cuts)	Ferrite (Tyler screen size cuts)	$\frac{(u_{mf})_{ferrite}}{(u_{mf})_{zirconia}}$
I	50^{-}–60^{+}	45^{-}–50^{+}	0.85
II	60^{-}–70^{+}	50^{-}–60^{+}	1.07
III	60^{-}–70^{+}	60^{-}–70^{+}	1.00
IV	80^{-}–100^{+}	70^{-}–80^{+}	1.05
V	100^{-}–120^{+}	80^{-}–100^{+}	0.94
VI	120^{-}–140^{+}	100^{-}–120^{+}	1.00

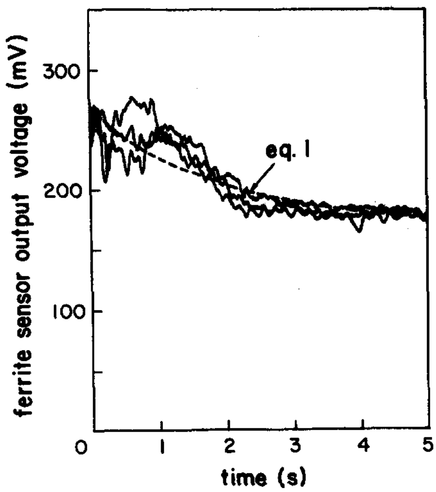

FIG. 7. Typical response curves for the cold mixing studies.

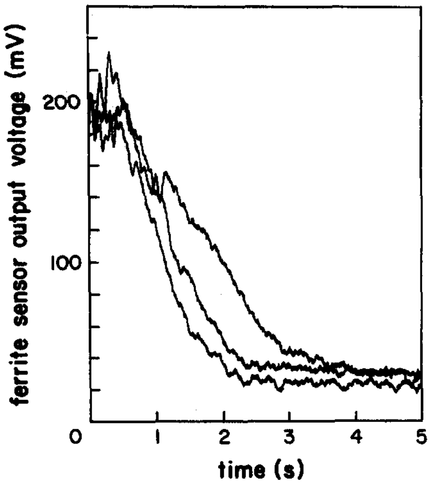

FIG. 8. Typical response curves for the hot mixing studies.

EXPERIMENTAL PROCEDURE

Cold mixing studies in a fluidized bed

Preliminary work indicated that the distribution of ferrite particles in the bed influenced the response of the ferrite sensor, the signal being greater if the particles were close together, in a clump, than when the particles were homogeneously dispersed in the bed. For this reason it was decided to carry out a study on the response of the sensor to a cold sample of ferrite being injected into a cold fluidized bed. Three replications of this cold mixing experiment were made for each zirconia–ferrite combination given in Table 1. A typical set of results is shown in Fig. 7 where it can be seen that the signals from the sensor (recorded at 250 Hz) show an approximately exponential decay with a time constant of the order of 1 s. The voltage output was modelled as an exponential decay of the following form:

$$V = A_1 + B_1 \exp(-C_1 t) \tag{1}$$

and the constants A_1, B_1 and C_1 were fitted using a least squares error criterion for each pair of ferrite–zirconia particles used.

Hot mixing studies in a fluidized bed

Similar experiments to those carried out in the previous section were performed but using a fluidized bed at approximately 90°C. Before injecting the particles the thermocouples in the bed were monitored to ensure that steady state had been reached. The output voltage from the ferrite was recorded at 250 Hz using the microswitch on the injection device to synchronize the start of the data acquisition with the injection of the particles. Some typical response curves for the hot mixing studies are given in Fig. 8. It can be seen from these curves that there is a rapid drop in output voltage from the ferrite sensor consistent with the heating of the ferrite particles and the consequent drop in magnetic permeability.

The decay of the response curves shown in Fig. 8 is due to two processes. The first is the loss in magnetic permeability due to the increase in temperature of the injected ferrite particles. The second effect is the dispersion of the clump of injected particles in the fluidized bed which was addressed in the cold mixing studies. If the raw data from the hot mixing studies are divided by a scaled form of equation (1) namely

$$\frac{V}{V_\infty} = 1 + \frac{B_1}{A_1} \exp(-C_1 t) \tag{2}$$

then a new curve will result. This adjusted curve now represents the curve which would have been obtained if the clumping of the injected particles had no effect on the output voltage from the sensor. The assumption used here is that the rate of dispersion of the injected particles is not influenced by the temperature of the fluidized bed, which is reasonable for this experiment. Thus this adjusted curve represents the true heating curve for the injected sample of ferrite particles. An example of this adjusting procedure is shown in Fig. 9.

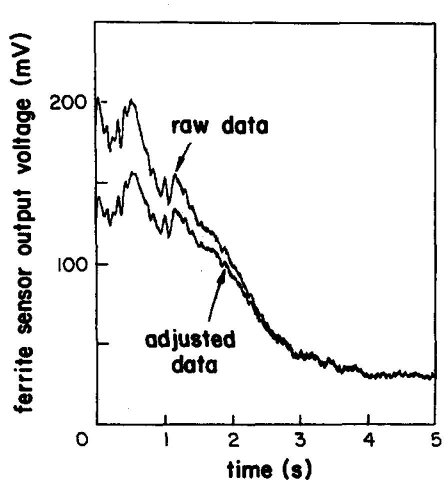

FIG. 9. The effect of adjusting the data to take account of the mixing of injected ferrite.

ANALYSIS OF DATA

Formulation of mathematical model

In the following section a simple analysis is presented to take into account the effects of the size distribution of particles comprising the injected sample and the small lags associated with the electronic equipment. Throughout this analysis it is assumed that the particles are isothermal and have no radial temperature distribution. This assumption is justified by the fact that the Biot numbers for the particles used in this study are very small, typically less than 0.005. Another assumption made in this analysis is that the heat transfer coefficient h_p is the 'true' particle–gas heat transfer coefficient for a single particle immersed in a fluidized bed. It will be shown, however, that the value of h_p obtained from this analysis is not this 'true' particle–gas coefficient but some averaged value for the particle in the clump of cold injected particles. The consequence of this assumption along with ways to alleviate it are presented in the section on the discussion of preliminary results.

For a single isothermal particle initially at some temperature T_i which is suddenly exposed to a hot medium at temperature T_f at time $t = 0$, the temperature of the particle T at any time t is given by

$$\frac{T_f - T}{T_f - T_i} = \exp\left\{-\frac{h_p}{L\rho_s}\frac{t}{C_{p,s}}\right\}. \tag{3}$$

Now the output voltage from the ferrite sensor for a given weight of sample of uniformly distributed ferrite in a bed of zirconia is given (from Fig. 2) as

$$\begin{aligned} V &= A + BT, & T &\leqslant T_c \\ V &= C\exp(-DT), & T &> T_c \end{aligned} \tag{4}$$

where the curie temperature (T_c) is taken to be the temperature at which the magnetic permeability of the ferrite first starts to decrease, and from Fig. 2 is approximately 67°C.

By substituting equation (3) in equation (4) we obtain

$$V = A + B\left[T_f - (T_f - T_i)\exp\left\{-\frac{h_p}{L\rho_s}\frac{t}{C_{p,s}}\right\}\right], \quad T \leqslant T_c$$

$$V = C\exp\left[-D\left(T_f - (T_f - T_i)\exp\left\{-\frac{h_p}{L\rho_s}\frac{t}{C_{p,s}}\right\}\right)\right], \quad T \geqslant T_c \tag{5}$$

or simply

$$V = g(L, t).$$

Thus knowing the particle size L we can predict the output voltage as a function of time from equation (5).

In practice the relationship given in equation (5) may not be sufficient to describe the response. Two more factors which affect the output, and as yet unaccounted for, are

(a) size distribution of particles;
(b) time lag of the electronic equipment.

As mentioned previously the different ferrite samples injected into the fluidized beds were narrow size cuts between adjacent Tyler screen sieves. It was assumed that the mass distribution of particles was uniformly distributed between the maximum L_2 and the minimum L_1 sizes of particles in the sample thus

$$\begin{aligned} P_x(L) &= \frac{1}{L_2 - L_1}, & L_1 &\leqslant L \leqslant L_2 \\ &= 0, & &\text{otherwise} \end{aligned} \tag{6}$$

where $P_x(L)$ is the mass fraction probability density function.

The electronic equipment, namely the ferrite sensor, has a time lag associated with it. This lag can be accurately represented by a first-order system with time constant τ_1. The input and output signals from the ferrite sensor may therefore be related by the following convolution integral:

$$\begin{aligned} V_{out}(t) &= \frac{1}{\tau_1}\int_0^t V_{in}(t)\exp\left\{-\frac{(t-\tau)}{\tau_1}\right\}\mathrm{d}\tau \\ &= \int_0^t V_{in}(t)E(t-\tau)\,\mathrm{d}\tau \end{aligned} \tag{7}$$

where

$$E(t-\tau) = \frac{1}{\tau_1}\exp\left\{-\frac{(t-\tau)}{\tau_1}\right\}.$$

The value of τ_1 measured for the ferrite sensor was 0.012 s and has only a small effect in these experiments.

By combining equations (5)–(7) we obtain the predicted output voltage from the ferrite sensor taking into account the heating of the particle, the change in magnetic permeability, the effect of different size particles and the effect of time lags in the electronic equipment. Thus

$$V_{out}(t) = \int_0^t \int_{L_1}^{L_2} E(t-\tau)g(L,\tau)P_x(L)\,\mathrm{d}L\,\mathrm{d}\tau. \tag{8}$$

On introducing the experimentally determined parameters into equation (8) the only unknown is h_p. Thus if a value of h_p is assumed then equation (8) can be integrated numerically and the ferrite sensor output voltage generated as a function of time. The profile generated in this way can then be compared with the experimentally measured profile and the value of h_p which minimizes the sum of squares error between the data and the model is taken to be the best estimate of the true heat transfer coefficient. Details of the parameter estimation and numerical integration and regression are given elsewhere [19] but some preliminary data and model profiles are compared in Fig.

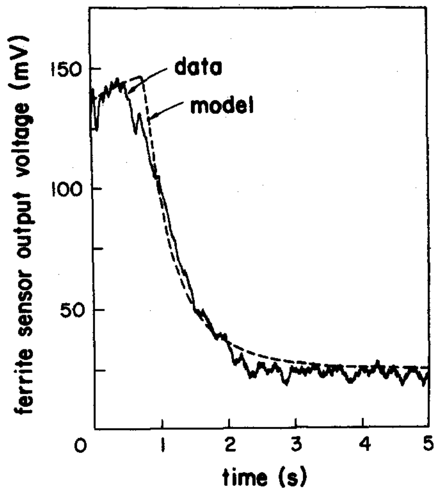

FIG. 10. Comparison of adjusted data and model for a hot mixing experiment.

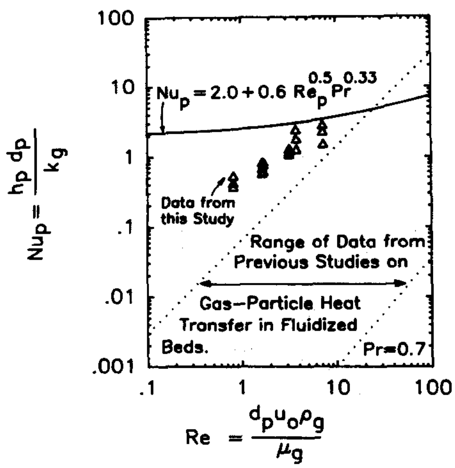

FIG. 11. Preliminary results of study compared with previously reported fluid particle heat transfer data in fluidized beds.

10. The general trend between the model and data is good although there is some error in the scaling which may be accounted for by slight amplifier drift in the equipment occurring between different experiments.

DISCUSSION OF PRELIMINARY RESULTS

The preliminary experimental results for the zirconia and ferrite pairs given in Table 1 are presented in Fig. 11. It can be seen that these data lie below the Ranz and Marshall [18] equation for single spheres in air but well above most other experimenters. The believed reason for the results being below the Ranz and Marshall equation is that the injection method is imperfect and that the dispersion time for the clump of particles is of the same order of magnitude as the characteristic heating time for the individual particles. It is believed that this effect causes the overall heating process to be slower, i.e. the heating of the particles in the middle of the clump takes longer than for those on the outside since the former are shielded. Thus the h_p values obtained in these experiments are some spacial average value for the clump as it breaks up. This problem can be alleviated by a more rapid injection and mixing of particles in the fluidized bed. For the case when the mixing of the injected particles takes place very quickly, i.e. much faster than the thermal relaxation time of the injected particles, the above analysis will yield the true particle–gas heat transfer coefficient. At present an improved method of particle injection is being sought.

CONCLUSIONS

An experimental method has been described which makes use of the change in magnetic properties to trace the temperature history of a sample of cold particles injected into a hot fluidized bed. The heat transfer coefficient can be back calculated from the experimental results with a simple model based on fundamental assumptions.

Although the technique was only applied to fluidized beds it could be easily applied to other multiphase systems.

The current particle injection technique produces slow dispersion of the injected sample in the bed with a characteristic mixing time of about 1 s, and this may cause considerable masking of the heat transfer effects.

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UNE METHODE EXPERIMENTALE POUR DETERMINER LE COEFFICIENT DE TRANSFERT THERMIQUE ENTRE DE FINES PARTICULES FLUIDISEES ET L'AIR A TRAVERS DES CHANGEMENTS DE PROPRIETES MAGNETIQUES

Résumé—On décrit une nouvelle technique expérimentale pour évaluer les coefficients de transfert thermique gaz–particule. La technique utilise le changement de propriétés magnétiques d'une ferrite à bas point de Curie et le suivi du changement de température d'un échantillon de particules froides injectées dans un lit fluidisé chaud. Ce lit a un diamètre de 28 mm et il est entouré d'une spire de détection qui est capable de déceler le changement de propriétés magnétiques de matériaux présents dans le lit. Un modèle est développé qui relie le signal de tension, en sortie de la spire de détection, au coefficient de transfert thermique gaz–particule. Des résultats expérimentaux préliminaires sont comparés à ceux du modèle.

EINE EXPERIMENTELLE METHODE ZUR ERMITTLUNG DES WÄRMEÜBERGANGSKOEFFIZIENTEN ZWISCHEN KLEINEN FLUIDISIERTEN PARTIKELN UND LUFT MITTELS ÄNDERUNGEN DER MAGNETISCHEN STOFFEIGENSCHAFTEN

Zusammenfassung—Ein neues experimentelles Verfahren zur Bestimmung des Wärmeübergangs-Koeffizienten zwischen Gas und kleinen Partikeln in einem Fließbett wird beschrieben. Das Verfahren benutzt die Änderung der magnetischen Stoffeigenschaften eines Ferrites mit niedrigem Curie-Punkt, um die sich ändernde Temperatur von in ein heißes Fließbett injizierten kalten Partikeln zu verfolgen. Das Bett hat einen Durchmesser von 28 mm und ist von einer Spule umgeben, die Änderungen der magnetischen Stoffeigenschaften des im Bett enthaltenen Materials detektieren kann. Ein Modell wurde entwickelt, welches die Ausgangsspannung der Spule und den Wärmeübergangs-Koeffizienten zwischen Gas und Partikeln in Beziehung setzt. Vorläufige experimentelle Ergebnisse werden mit dem Modell verglichen.

ЭКСПЕРИМЕНТАЛЬНЫЙ МЕТОД ОПРЕДЕЛЕНИЯ КОЭФФИЦИЕНТА ТЕПЛОПЕРЕНОСА МЕЖДУ ПСЕВДООЖИЖЕННЫМ СЛОЕМ МЕЛКИХ ЧАСТИЦ И ВОЗДУХОМ ПУТЕМ ИЗМЕНЕНИЯ МАГНИТНЫХ СВОЙСТВ

Аннотация—Описан новый экспериментальный метод определения коэффициентов теплопереноса между газом и частицами в псевдоожиженных слоях мелких частиц. Метод основан на изменении магнитных свойств феррита с низкой точкой кюри и позволяет проследить за изменением температуры порции холодных частиц, введенных в нагретый псевдоожиженный слой. Слой диаметром 28 мм помещен в детекторную катушку, способную улавливать изменение магнитных свойств материала слоя. Разработана модель, связывающая сигнал напряжения на выходе из детекторной катушки с коэффициентом теплопереноса между газом и частицами. Проводится сравнение предварительно полученных экспериментальных данных с моделью.